The Great Observatories Origins Deep Survey

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Abstract. The Great Observatories Origins Deep Survey (GOODS) is designed to gather the best and deepest multiwavelength data for studying the formation and evolution of galaxies and active galactic nuclei, the distribution of dark and luminous matter at high redshift, the cosmological parameters from distant supernovae, and the extragalactic background light. The program uses the most powerful space– and ground–based telescopes to cover two fields, each $10' \times 16'$, centered on the Hubble Deep Field North and the Chandra Deep Field South, already the sites of extensive observations from X–ray through radio wavelengths. GOODS incorporates 3.6–24μm observations from a *SIRTF* Legacy Program, four–band ACS imaging from an *HST* Treasury Program, and extensive new ground–based imaging and spectroscopy. GOODS data products will be made available on a rapid time–scale, enabling community research on a wide variety of topics. Here we describe the project, emphasizing its application for studying the mass assembly history of galaxies.

1 Introduction

This conference, and this volume of contributions, demonstrate the vital interest in understanding the mass assembly history of galaxies. Theory provides guidance about how dark matter halos are built up in a hierarchical process largely controlled by the power spectrum of density fluctuations and the parameters of the cosmological world model. The assembly of the stellar content of galaxies is governed by more complex physics, including gaseous dissipation, the mechanics of star formation itself, and feedback due to the energetic output from stars and AGN on the baryonic material within galaxies.

Deep imaging and spectroscopic surveys now routinely find and study galaxies throughout most of cosmic history, back to redshifts $z = 6$ and earlier. However, observations are only now beginning to provide constraints on galaxy mass assembly, particularly at $z > 1$. For example, the stellar mass assembly history is characterized by the evolving distribution of masses ($\mathcal{M}$) and star formation rates (SFR, or $\dot{\mathcal{M}}$) with time or redshift, $f(\mathcal{M}, \dot{\mathcal{M}}, t)$. Most investigations to date have considered only moments over this distribution, such as luminosity functions (an imperfect surrogate for the mass distribution) or the global star formation rate SFR(z). Moreover, at high redshift, $\mathcal{M}$ and $\dot{\mathcal{M}}$ are at best only imperfectly measured using currently available observables. Starlight traces stellar mass only in an indirect manner: the mass–to–light ratio ($\mathcal{M}/L$) of a mixed stellar population depends on many parameters, including its age, past star formation history, initial mass function (IMF), dust extinction, and metallicity.

Locally, the best constraints come from measurements at near–infrared wavelengths [1,2], where the longer–lived stars which dominate the mass contribute most to the galaxy luminosity. Moreover, the effect of dust extinction is smaller at redder wavelengths. For $\dot{\mathcal{M}}$, no one observable provides a direct and "universal" tracer of star formation in all circumstances. Ultraviolet, mid– and far–infrared, radio, and nebular line emission are all valuable tools for measuring star formation, with different dependences on extinction, IMF, etc., and thorough surveys of high redshift star formation require the use and cross–calibration of multiple indicators.

2 The Great Observatories Origins Deep Survey

The Hubble Deep Fields (HDF–N and HDF–S [3,4,5]) provided an invaluable resource of public data for studying faint, distant galaxies. Moreover, they served as a catalyst for follow–up observations at many wavelengths using the most powerful telescope facilities in space and on the ground. However, the HDFs have their limitations. First, they are very small fields, 5 arcmin^2 each, probing very small co–moving volumes. Second, the HDF–S followed the HDF–N by several years. This diluted its impact somewhat, and reduced motivation for the vital follow–up studies needed to verify HDF–N results and to test their robustness against line–of–sight variations due to galaxy clustering. Third, the wavelength range $\lambda\lambda$3–1000μm is the "weak link" in HDF coverage. ISO data at 7 and 15μm [6,7] and SCUBA measurements at 850μm [8] probe mid– and far–IR emission, but can detect only the most luminous dust–obscured objects at high redshift. HDF studies of galaxies at $z > 1$ are therefore missing important information at mid– and far–infrared wavelengths where most of the bolometric luminosity from star formation is believed to emerge, as well as the redshifted near–infrared rest–frame light ($\lambda\lambda$3–10μm) which most nearly traces total stellar mass.

The Great Observatories Origins Deep Survey (GOODS) follows in the footsteps of the HDF projects, and is a campaign to unite the best, deepest data across the electromagnetic spectrum to create a community resource for exploring the distant universe. GOODS data will be used to study the formation and evolution of galaxies, the radiative output from active galactic nuclei and star formation at high redshift, the characteristics of the extragalactic background light, large scale structure and the distribution of dark matter, the values of the cosmological parameters, and many other projects outside the scope of its core design.

GOODS builds upon existing or ongoing surveys from space– and ground–based facilities, including NASA's Great Observatories, *HST*, *Chandra* and *SIRTF*. The program targets two fields, each $10' \times 16'$, around the Hubble Deep Field North (HDF–N) and the Chandra Deep Field South (CDF–S). These are the most data–rich and well–studied deep survey areas on the sky, with extensive near–infrared and optical imaging and spectroscopy, highly sensitive radio and sub–mm measurements, and the deepest X–ray observations from *Chandra* [9,10] and *XMM–Newton* (in progress; PIs: Bergeron (CDF–S); Jansen and Grif-

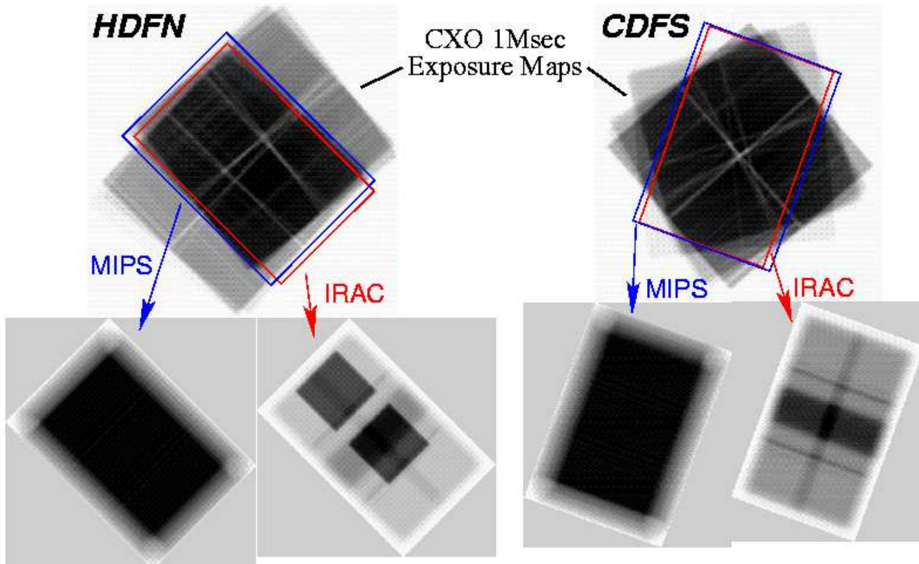

Fig. 1. Layout of the GOODS/*SIRTF* fields. The upper panels show the exposure maps for the 1 Msec *Chandra* X–ray observations of the HDF–N and CDF–S. Boxes show the approximate boundaries of the *SIRTF* IRAC and MIPS survey areas (roughly $10' \times 16'$). Insets below show the nominal *SIRTF* exposure time maps. The HDF–N includes "ultradeep" IRAC observations, which are contingent upon on–orbit tests to establish the practical sensitivity limit of the instrument.

fiths (HDF–N)). Two fields, one in each celestial hemisphere, provide insurance against variance due to line–of–sight clustering effects, and enable follow–up programs by astronomers and observatories worldwide.

2.1 The *SIRTF* Legacy Program

The GOODS *SIRTF* Legacy Program (PI: Dickinson) will make the deepest observations with that facility at 3.6 to 24μm. Observations will be carried out in the first year of *SIRTF* operations, in 2003–2004. The bulk of the GOODS *SIRTF* program will use the Infrared Array Camera (IRAC), observing at 3.6, 4.5, 5.8 and 8.0μm with exposure times of 23.6 hours per band. A small overlap strip in each field will receive twice this integration time, and in the HDF–N only, a pair of $5' \times 5'$ "ultradeep" IRAC fields are planned with exposure times of 70 hours (reaching 94 hours in the maximum overlap region atop the WFPC2 HDF–N).

These long exposure times are essential in order to reach sensitivities $\lesssim 1\mu$Jy with reasonably high S/N ratios. For example, the IRAC 8μm observations will sample the rest–frame K–band light from Lyman break galaxies (LBGs) at $z \approx 3$, and will thus provide an important handle on their total stellar content. The

expected 8.0μm flux for an "L^*" LBG (with $\mathcal{M}_* \approx 10^{10}\mathcal{M}_\odot$ [11,12]) is 1.5μJy. At 3.6 and 4.5μm, the flux sensitivity achieved by the GOODS/IRAC observations will depend strongly on the achieved image quality (expected to be in the range 1.5–2.3 arcsec FWHM), since source confusion will be important – less so at 5.8 and 8.0μm, where the zodiacal background should set the flux limits. The ultradeep IRAC fields will probe farther down the luminosity and mass function at $z \sim 3$, and should detect typical objects at $z \approx 5$.

The GOODS fields will also be observed at longer wavelengths with the *SIRTF*/MIPS instrument. Deep ISOCAM 15μm imaging surveys were sensitive to redshifted 7.7μm PAH emission from star–forming galaxies at $z \approx 1$, and the GOODS 24μm observations are designed to detect objects with similar rest–frame luminosities at $z = 2$ to 2.5. In principle, they should be able to detect the mid–infrared emission from obscured star formation in typical Lyman break galaxies at these redshifts. The actual sensitivity achieved at 24μm will depend on the (presently uncertain) level of source confusion and on instrument performance. The GOODS program plans 10.4 hour exposures at 24μm, contingent upon on–orbit demonstration that they will reach substantially fainter flux limits than planned 20 min exposures from the MIPS GTO wide–field survey (PI: Rieke) which covers the GOODS fields. Test observations made early in the mission will be used to determine the longest exposure times practical for making confusion–limited observations of the GOODS fields. The *SIRTF* GTO program will also cover these fields at 70μm and 160μm, sensitive to the far–infrared thermal emission from high redshift, dust–obscured star formation.

2.2 The *HST*/ACS Treasury Program

The GOODS *HST* Treasury Program (PI: Giavalisco) will use the Advanced Camera for Surveys (ACS) to image the fields with four broad, non–overlapping filters, F435W (B), F606W (V), F775W (i), and F850LP (z), with exposure times of 3, 2.5, 2.5 and 5 orbits, respectively, reaching extended–source sensitivities within 0.5-0.8 mags of the WFPC2 HDF observations. The observations will be carried out during *HST* Cycle 11, in 2002–2003. GOODS is a deep survey, not a wide one, but is nevertheless much larger than most previous *HST*/WFPC2 programs. The GOODS fields cover 32× the solid angle of the combined HDF-N and S, and are 4× larger than the combined HDF Flanking Fields, and 2.5× larger than the WFPC2 Groth Strip Survey. The Viz observations will be taken in five repeat visits separated by approximately 45 days, enabling a search for SNe Ia at $1.2 < z < 1.8$ to test the apparent transition from cosmic deceleration to acceleration that is predicted in world models dominated by a cosmological constant (and suggested by current data [13]).

The z–band observations will image the optical rest–frame light from galaxies out to $z = 1.2$, with angular resolution superior to that from WFPC2. The $BViz$ imaging will also enable a systematic survey of Lyman break galaxies at $4 < z < 6.5$, reaching back to the suggested epoch of reionization [14,15]. The photometric depth and co–moving volume coverage will make it possible to quantify the LBG population in this redshift range with statistical accuracy comparable to that

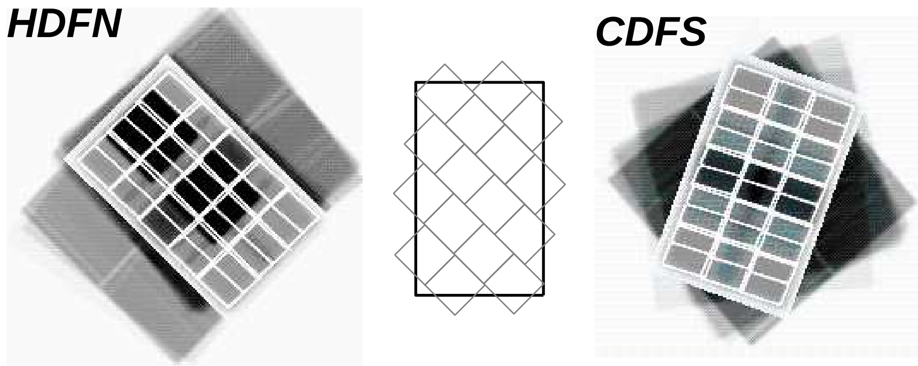

Fig. 2. Layout of the GOODS/*HST* observations. The grid of white boxes shows the tiling of *HST*/ACS fields at one telescope orientation, superimposed on the *Chandra* (outer greyscale) and *SIRTF* IRAC (inner greyscale) exposure maps. The fields will be revisited approximately every 45 days to enable a search for high redshift supernovae. The center inset schematically shows how the rotated ACS pointings from alternate visits will be tiled over the GOODS area.

now available from large, ground–based LBG surveys at $z \approx 3$ [16]. The ACS data will also provide a powerful tool for studies of gravitational lensing, low–mass stars in our galaxy, and perhaps objects in the outer solar system.

2.3 Ground–based observations

As noted above, the HDF–N and CDF–S are already among the most data–rich deep survey regions on the sky, and the GOODS program includes a large component of ground–based supporting observations to enable research on distant objects. In large, coordinated NOAO and ESO programs (PIs: Cesarsky, Dickinson), we are obtaining new optical and near–infrared imaging, including U–band imaging from the KPNO and CTIO 4m MOSAIC cameras, and JHK_s imaging with the KPNO 4m/FLAMINGOS and VLT/ISAAC instruments. We are also planning a spectroscopic campaign in the CDF–S using the new VIMOS and red–upgraded FORS–2 spectrographs on the VLT (see the contribution by Renzini et al. to these proceedings). This program will provide a public data resource of several thousand spectra and redshifts for galaxies in the southern GOODS field. We will also supplement the already–extensive HDF–N redshift data [17] and extend it over the whole GOODS/HDF–N using spectroscopy with Gemini–N/GMOS and Keck/DEIMOS+LRIS. We are collaborating on new ATCA radio observations of the GOODS/CDF–S (PI: Koekemoer), and JCMT/SCUBA observations of the GOODS/HDF–N (PIs: Barger, Scott). Table 1 provides a summary of observations being taken as part of the GOODS project, along with some other key data sets for the GOODS fields at other wavelengths.

Table 1. GOODS observations and complementary data sets. The top portion of the table lists GOODS space– and ground–based imaging observations at 0.36–24μm and their nominal sensitivities. The bottom portion is an incomplete list of additional observations available, in progress, or in preparation, which cover the GOODS areas.

Wavelength	Facility	Sensitivity (S/N=5)
0.36μm	KPNO+CTIO 4m	AB = 27.3 (U)
0.4-0.9μm	*HST*/ACS	AB = 27.9, 28.2, 27.5, 27.4[a] ($BViz$)
1.2-2.2μm	VLT, KPNO 4m	AB = 25.2, 24.7, 24.4 (JHK_s)
3.6-8.0μm	*SIRTF*/IRAC	AB = 24.5, 24.5, 23.8, 23.7 (0.6–1.2 μJy)[b]
24μm	*SIRTF*/MIPS	20-80 μJy[c]
Type	**Facility**	**Notes**
Spectroscopy	VLT, Gemini, Keck	Various PIs; GOODS programs & collabs.
X-ray	*Chandra*, *XMM*	Public *Chandra* data and *XMM* GTO progs.
70, 160μm	*SIRTF*/MIPS	*SIRTF* GTO program
Sub-mm	SCUBA, SEST	Various PI programs
Radio	VLA, ATCA	Various PIs; CDF–S observs. in progress

[a] For 0.5 arcsec diameter aperture
[b] IRAC deep survey, for "handbook" PSF; 3.6 and 4.5μm performance may be better
[c] Uncertain sensitivity; depends on instrument performance and source confusion

2.4 Data products

In the spirit of the HDF projects, the GOODS team will make data products available to the community on a rapid time–scale. The raw *SIRTF* and *HST* data will be available upon ingestion into the SSC and STScI archives. The reduced data products from both facilities will be provided in a series of incremental releases: "best effort" (version 0.5) reduced images two to three months after each observing epoch; improved (version 1) image mosaics three months after the final observations; and reprocessed (version 2) data products and multiwavelength catalogs six to twelve months after the final observations. Similar release schedules apply to the ancillary data from ESO and NOAO, and we will generally follow similar procedures for GOODS–related data from other facilities.

3 Science enabled by GOODS

A primary goal of the GOODS program is to provide observational data for tracing the mass assembly history of galaxies throughout most of cosmic history. First, this requires redshift information to sort galaxies by distance and

cosmic time. Much of this will come from the existing and planned spectroscopic surveys of these fields. At fainter fluxes, the 13–band GOODS imaging data, covering 4.5 wavelength octaves from 0.36–8μm, will provide an exceptional resource for estimating photometric redshifts for galaxies of all types, calibrated by the extensive spectroscopy.

The *SIRTF* IRAC data is designed to measure the rest–frame K–band starlight from "ordinary" galaxies (e.g., the progenitor fragments of the Milky Way) at $z \approx 3$, and can detect rest–frame near–infrared light ($\lambda > 1\mu$m) from objects out to $z = 7$. Photometry will trace the spectral energy distributions of galaxies from UV through IR rest–frame wavelengths, and thus constrain their stellar populations and $\mathcal{M}/L$, providing the best estimates (modulo assumptions about the IMF) of their total stellar masses. GOODS data, as well as other observing programs covering these fields, will offer a wide array of star formation indicators, including rest–frame UV and mid–infrared photometry, far–infrared measurements from the *SIRTF* GTO MIPS program, very deep radio and sub–mm surveys, and nebular line spectroscopy from the redshift surveys and targeted follow–up programs. These different indicators can be applied and cross–calibrated for the *same* high redshift galaxies, guided by detailed knowledge from galaxy surveys in the local universe, such as the SINGS *SIRTF* Legacy Program (PI: Kennicutt).

The *HST*/ACS program will provide high resolution imaging needed to relate the morphological properties of galaxies (size, surface brightness, Hubble type, etc.) to their stellar populations, masses, star formation rates, and AGN activity, tracing the emergence of the Hubble sequence and its relation to the physical characteristics of galaxy assembly. Future programs of high–dispersion spectroscopy can be used to measure galaxy kinematics which trace gravitational mass, connecting the stellar population properties traced by *SIRTF* and the dark matter potential wells. Weak and strong lensing measurements, as well as galaxy clustering, will also provide statistical constraints on dark halo mass on larger physical scales.

GOODS data will also provide an important resource for studying the evolution of active galactic nuclei, in particular to identify both obscured and unobscured AGN with "typical" luminosities (i.e., not just the most powerful QSOs and radio galaxies) out to high redshifts, back to the "QSO era" at $z > 2$. Deep X–ray data will sort AGN from starbursts as the engines powering mid– and far–IR emission in distant objects, enabling a census of energetic output from these mechanisms over a broad range of redshift. The *SIRTF* data will also fill an important gap in our measurements of the discrete source component of the extragalactic background light (EBL), the integral record of emission and absorption of radiation throughout cosmic history. IRAC data at 3.6–8μm will trace the "downside" of the peak of the direct stellar contribution to the EBL, while 24μm measurements (and GTO *SIRTF* data at 70 and 160μm) will follow the "upside" of the far–infrared peak due to dust–absorbed starlight and AGN emission.

4 Conclusion

The installation of ACS on board *HST*, the launch of *SIRTF*, and the implementation of a new generation of massively multiplexed spectrographs on large ground–based telescopes will open rich new opportunities for observing galaxy formation and evolution, out to very high redshift and early cosmic epochs. The GOODS project is designed to bring all of these tools to bear on common deep survey fields, uniting the best observations at all accessible wavelengths. These data will be gathered into a coherent archive for public release, enabling community research on a wide variety of topics. We hope that at future meetings such as this one, GOODS data will have helped to advance our understanding of galaxy masses at high redshift, and of the history of galaxy assembly.

More information about the project and observing program can be found on the GOODS web sites at STScI (`http://www.stsci.edu/science/goods`) and ESO (`http://www.eso.org/science/goods`).

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